DTU Library

Reversible electrochemical power plants for 100% renewable electricity and fuels

Graves, Christopher R.

Publication date:
2011

Document Version
Publisher's PDF, also known as Version of record

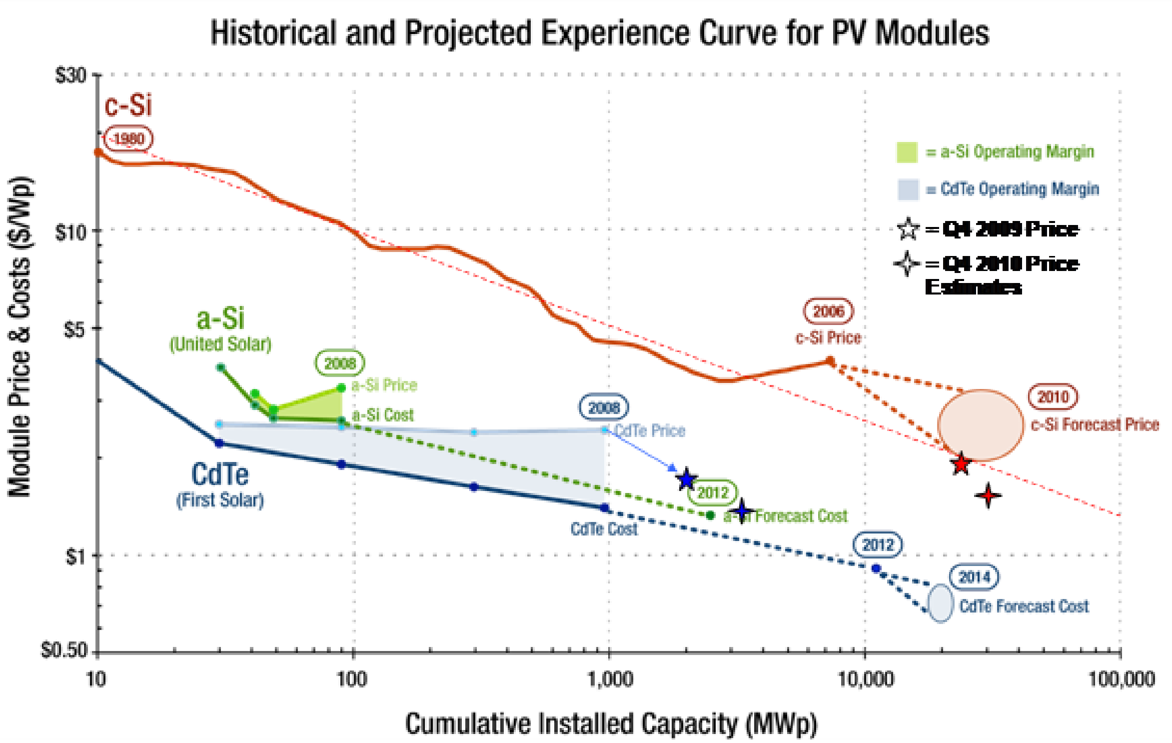
Reversible electrochemical power plants for 100% renewable electricity and fuels

Chris Graves
Post-doc, Fuel Cells & Solid State Chemistry Division, Risø DTU
cgra@risoe.dtu.dk / christoph.graves@gmail.com

April 15th, 2011 Workshop
"Capture and conversion of CO_2 into sustainable hydrocarbon fuels"
Roskilde, Denmark

Switching to 100% renewable energy

- Affordable large-scale renewable energy is coming within reach



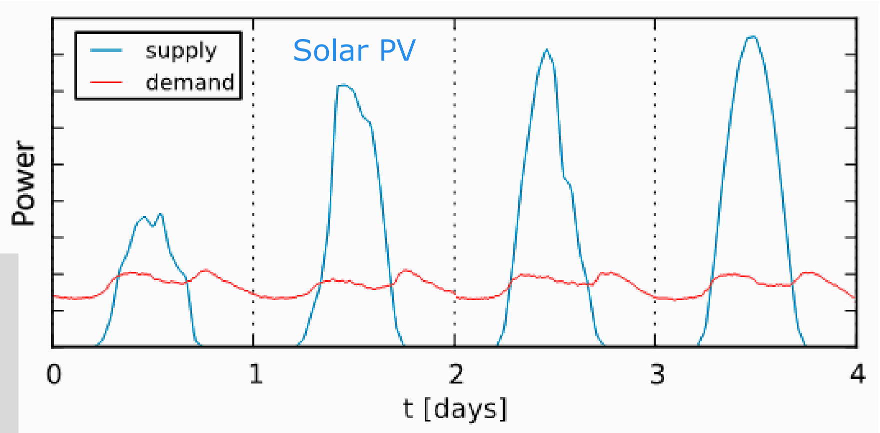
[*U.S. DOE SETP presentation, 2009*]

Switching to 100% renewable energy

Meeting 100% of demand

- Electricity – needs storage:
- Fuels – are storage

Although other load-balancing methods like demand-side management are helpful, storage is ultimately needed.



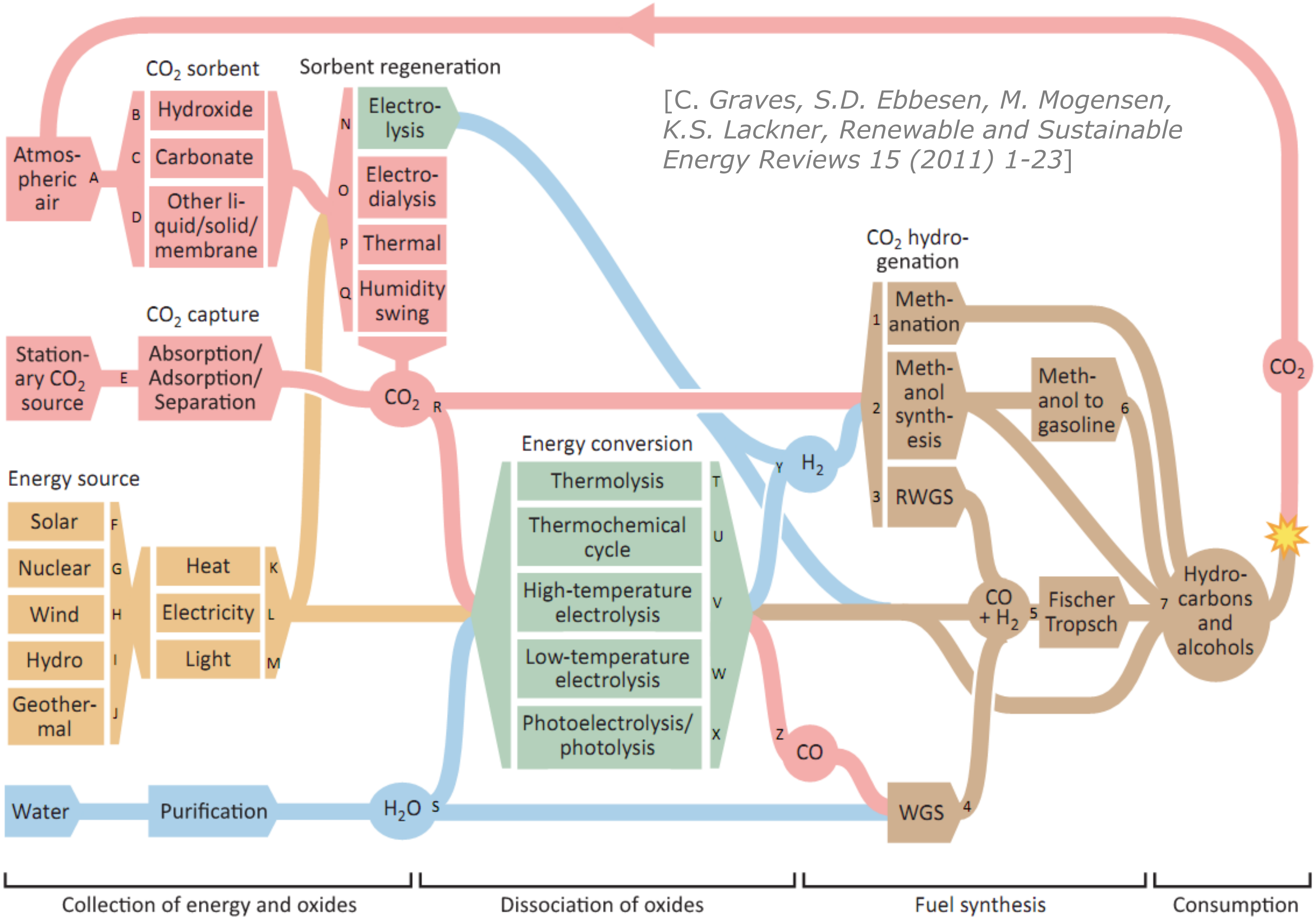
- We *can* do without any biomass/biofuels

- Topic at hand: transition to and support an energy economy based entirely on intermittent renewable electricity sources

- Specifically, a system based on reversible fuel cells

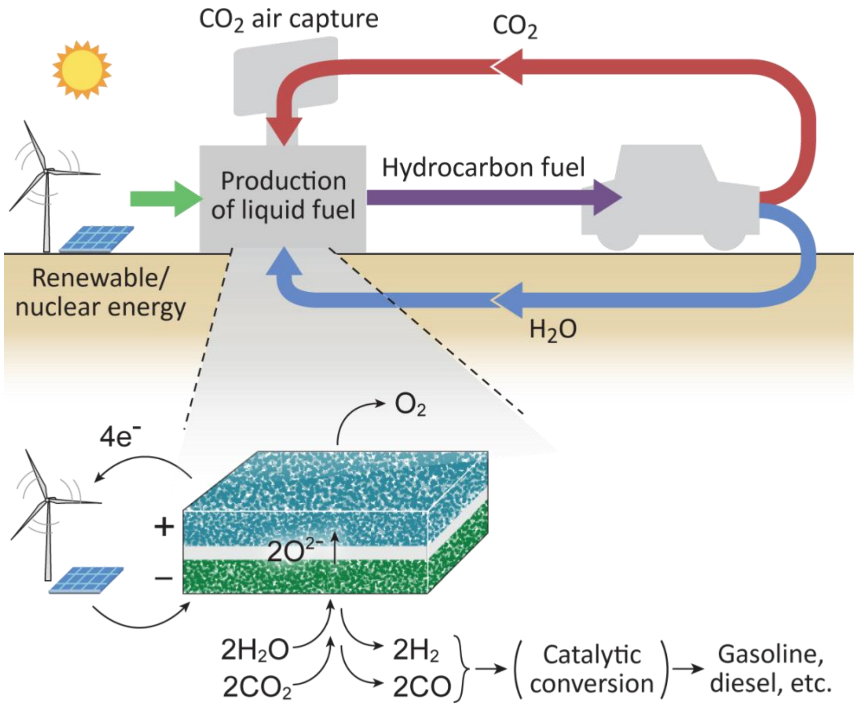
Related prior work (CO_2-to-fuels)

- Possible methods to convert CO_2 into fuels (many presented in this workshop)



Related prior work (CO_2-to-fuels)

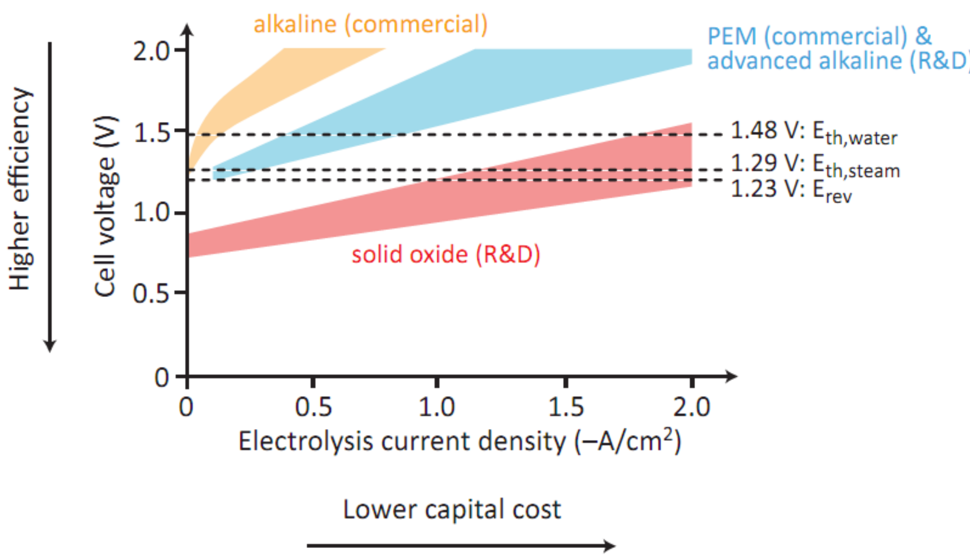
Detailed analysis of a particular electrolysis-based pathway



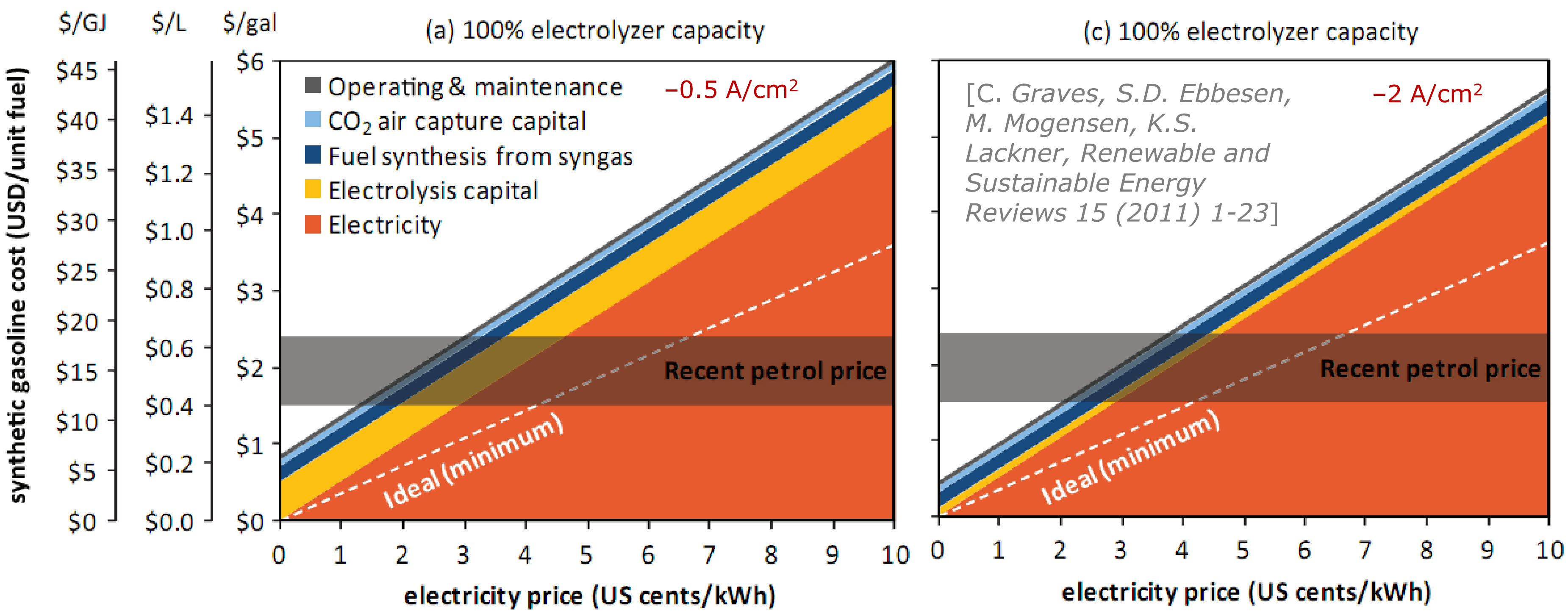
[C. *Graves, S.D. Ebbesen, M. Mogensen, K.S. Lackner, Renewable and Sustainable Energy Reviews 15 (2011) 1-23*]

High temp. co-electrolysis of H_2O and CO_2

- makes very efficient use of electricity and heat (near-100% electricity-to-syngas efficiency)
- provides high reaction rates
- directly produces syngas (CO/H_2 mix-ture) for use in conventional catalytic fuel synthesis reactors.



Related prior work (CO_2-to-fuels)

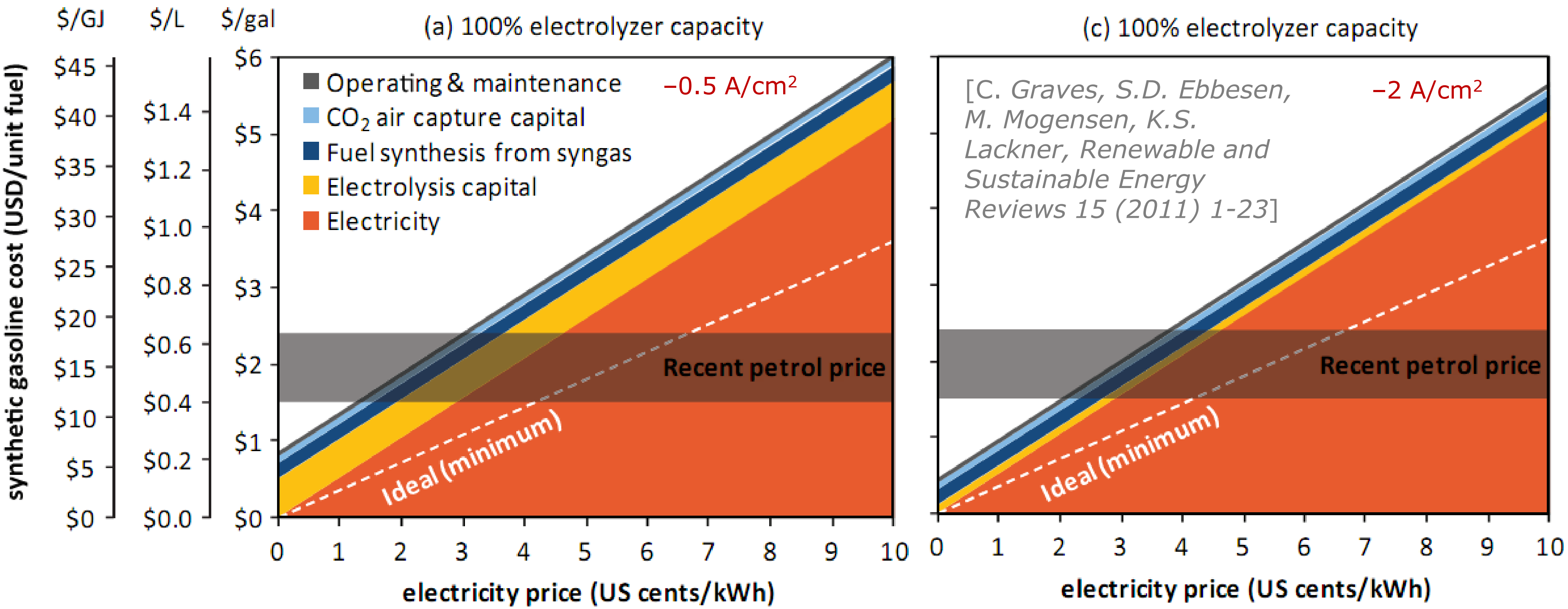


Fuel production economics is promising…

Re. choice of "safe" and "harsh" current densities:

- *Sune's talk yesterday*
- *Graves, Ebbesen, Mogensen 2010 doi: 10.1016/j.ssi.2010.06.014*
- *Knibbe, Traulsen, Hauch, Ebbesen, Mogensen 2010 doi: 10.1149/1.3447752*
- *Ebbesen, Graves, Hauch, Jensen, Mogensen 2010 doi: 10.1149/1.3464804*
- *Ebbesen & Mogensen 2010, doi: 10.1149/1.3455882*

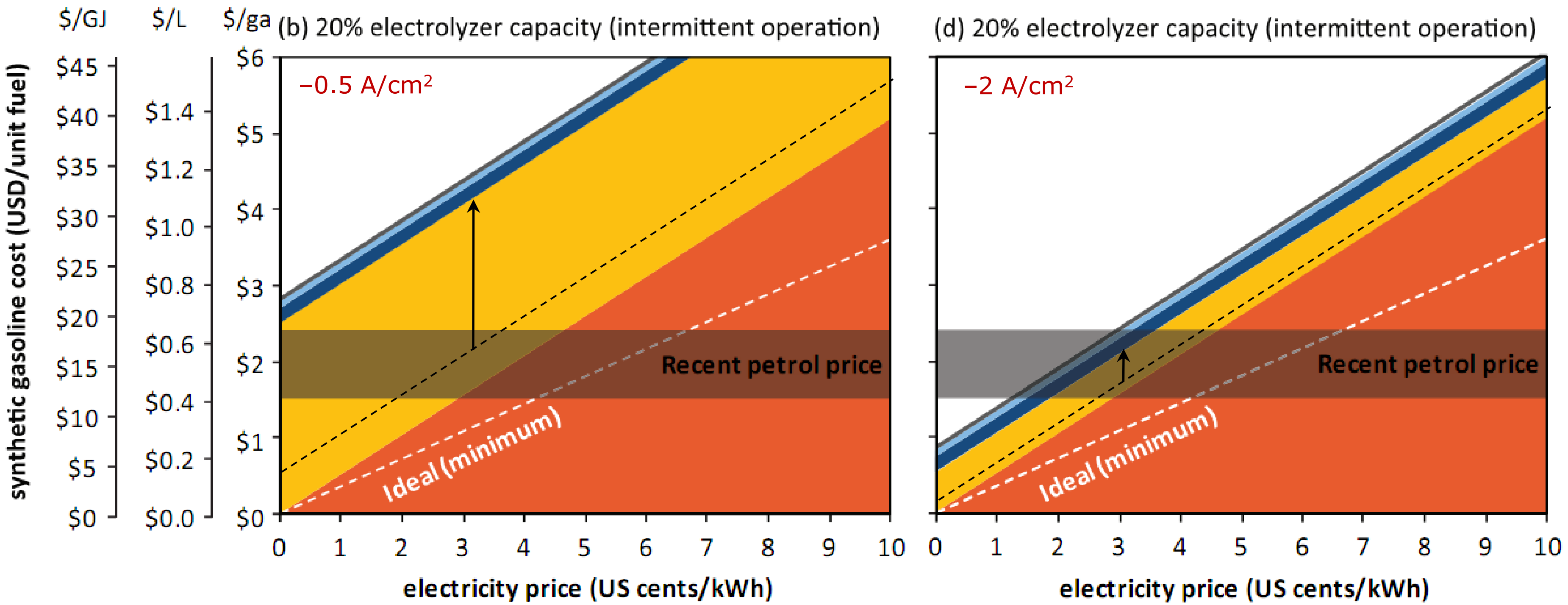
Related prior work (CO_2-to-fuels)



Fuel production economics is promising…

- Leads to consider whether converting fuels back to electricity could be affordable
- If we will turn around and convert it right back to electricity, need not be convenient, portable, high energy density and plug into existing infrastructure – need not be liquid hydrocarbon storage.

Related prior work (CO_2-to-fuels)



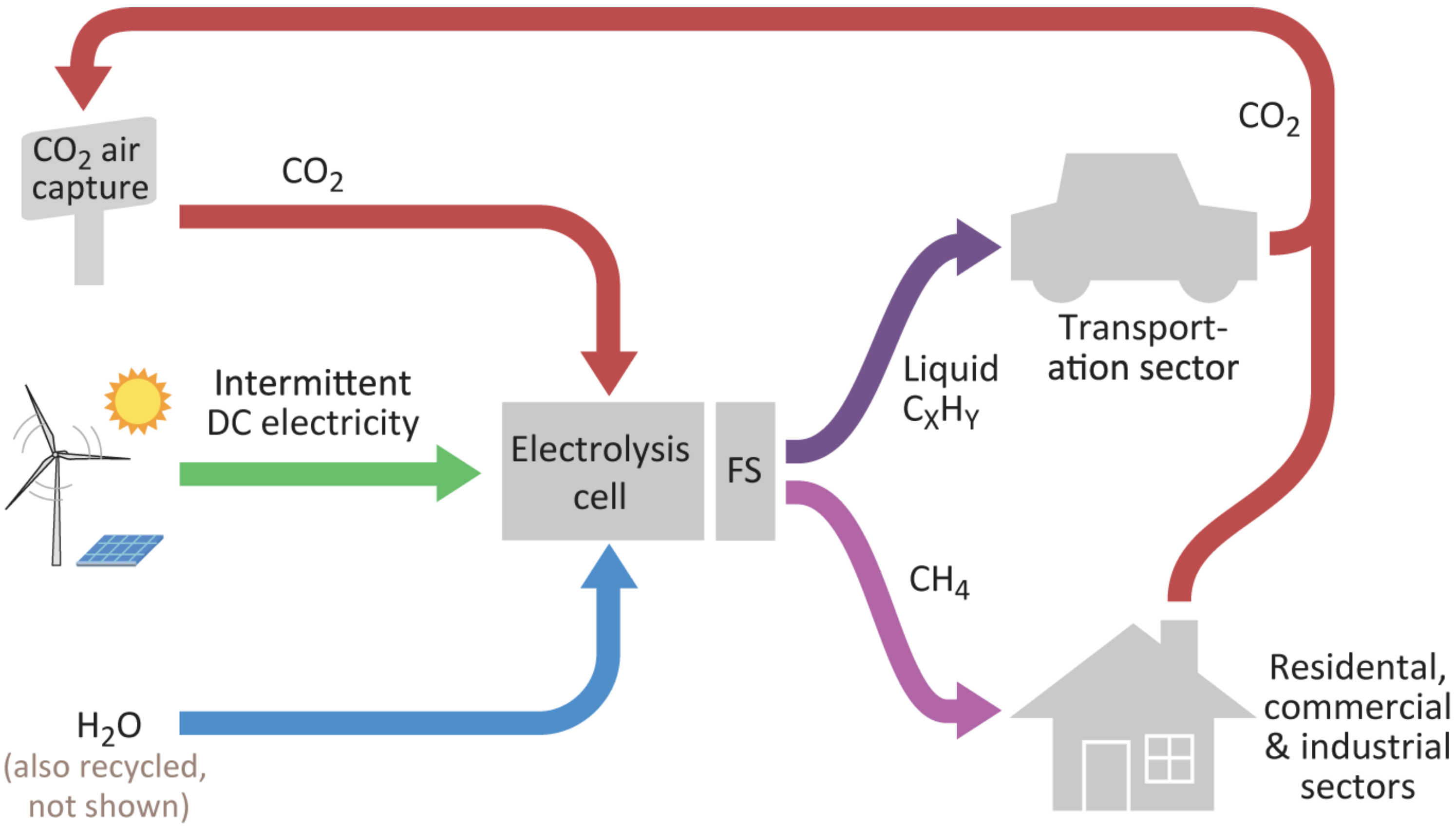
- But keep in mind the importance of capacity factor!

  Since intermittent renewable energy is the large-scale long-term source.

Does this story change if fuel production is integrated with electricity storage-retrieval (reversible operation)?

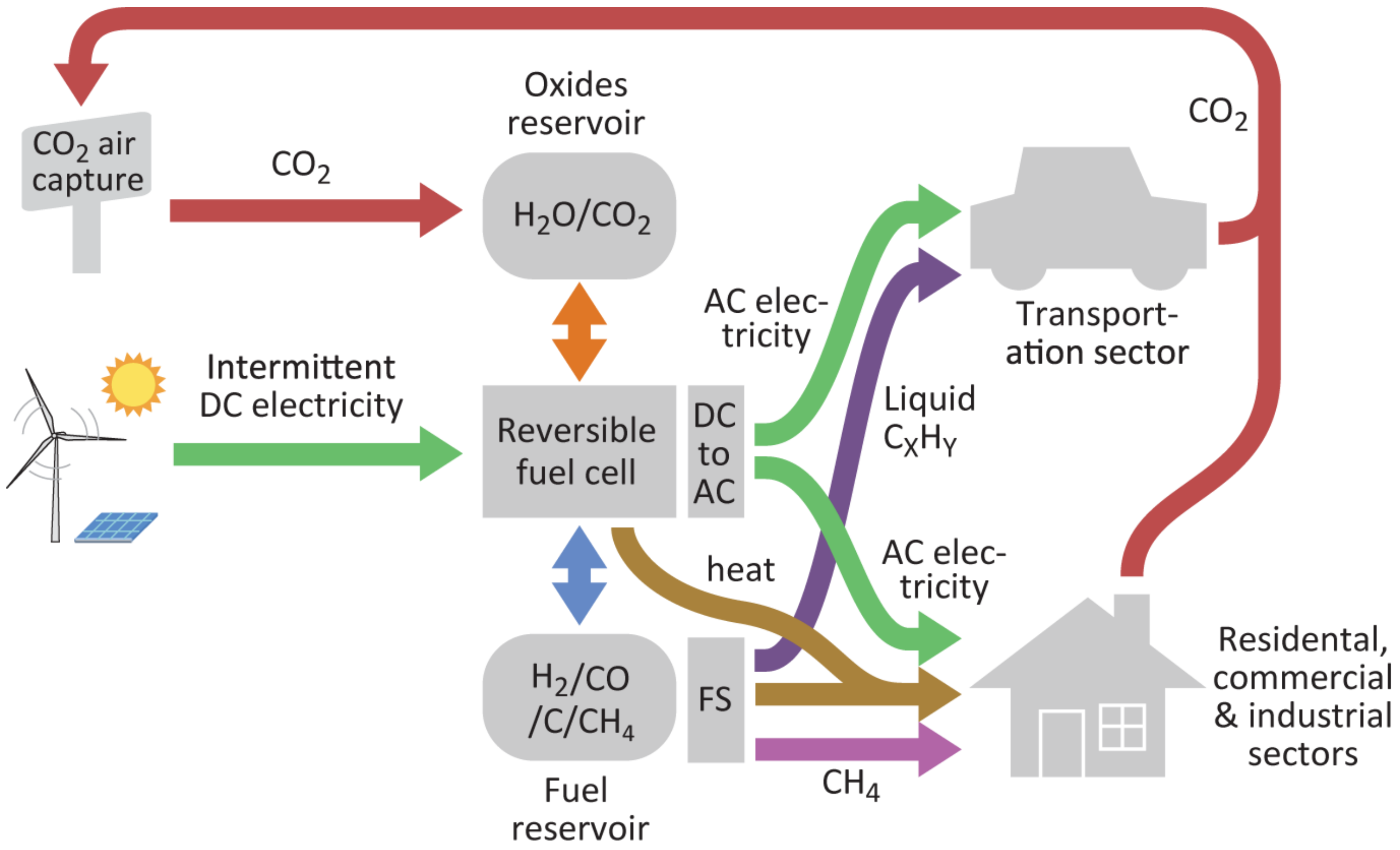
Reversible fuel cells

Intermittent electricity → hydrocarbon fuels



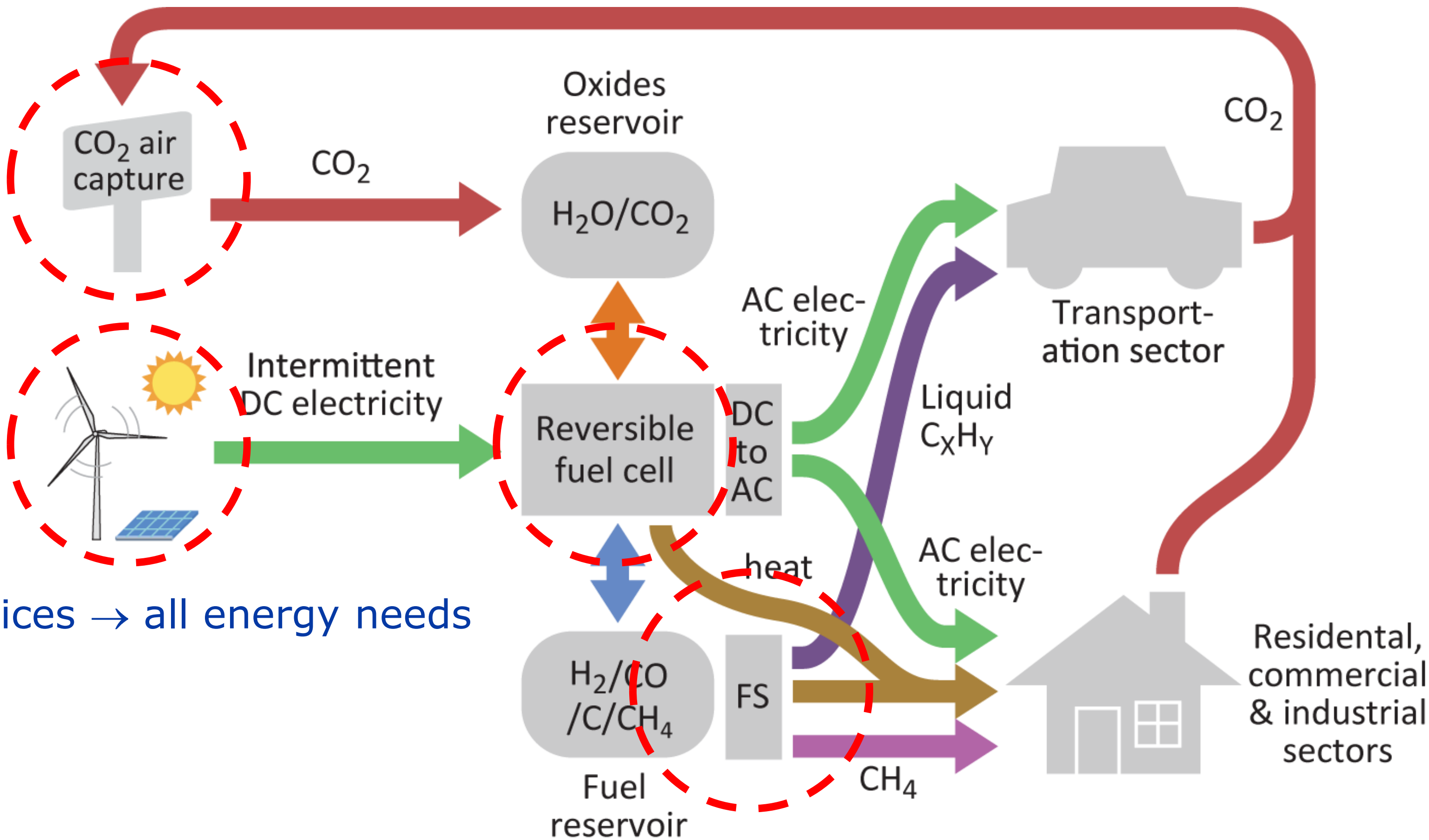
Reversible fuel cells

Intermittent electricity → hydrocarbon fuels + on-demand electricity



Reversible fuel cells

Intermittent electricity → hydrocarbon fuels + on-demand electricity



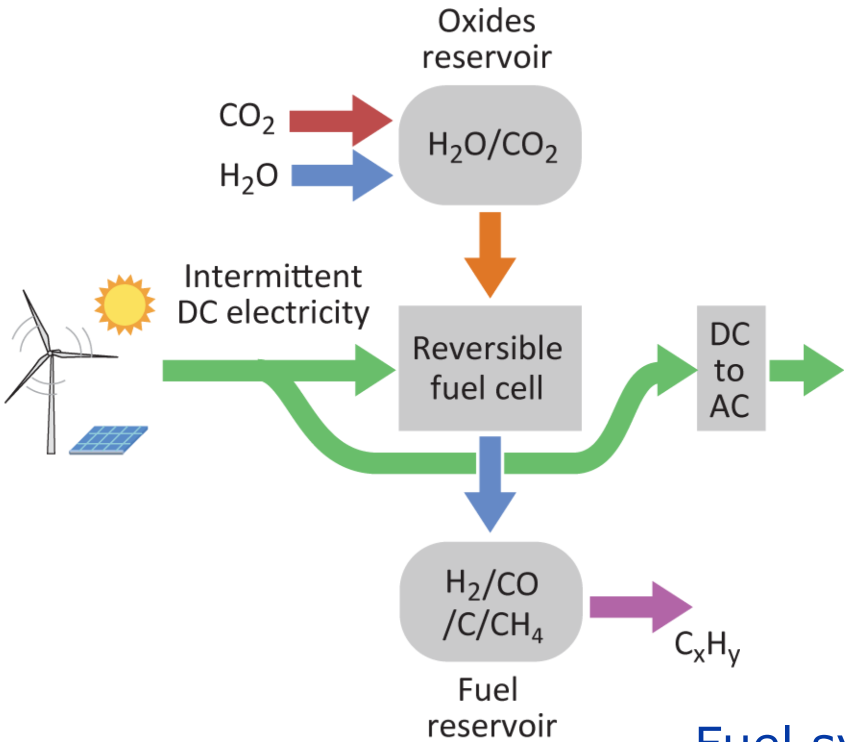
4 devices → all energy needs

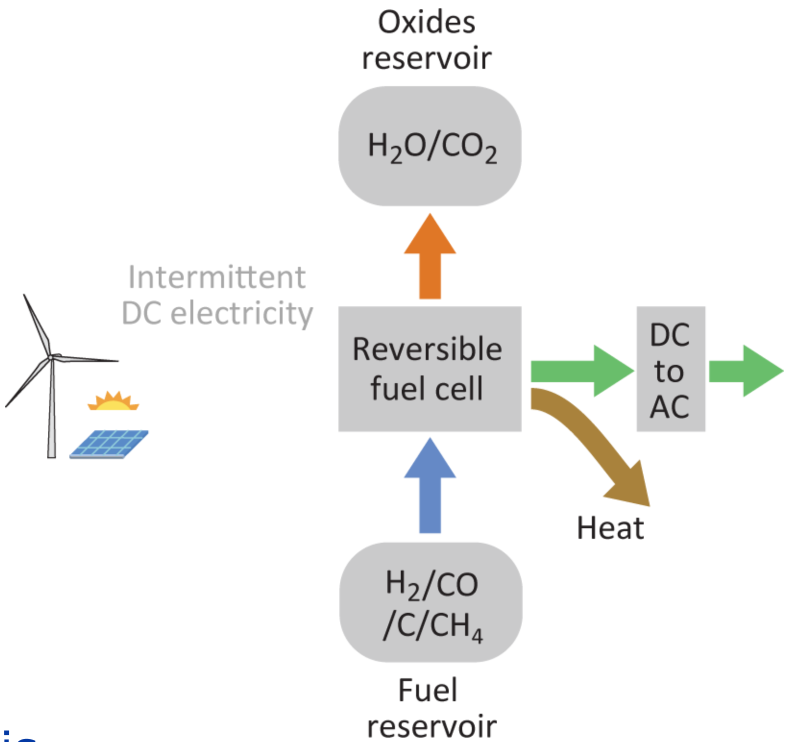
Reversible fuel cells

Charge mode
(electrolysis)
(supply > demand)

Similar to a flow battery. But can a flow battery…

Discharge mode
(fuel cell)
(supply < demand)





Fuel synthesis
(additional supply)

Reversible fuel cells

Concept has been proposed before, but not examined in any detail
(which is sometimes where the devil is)

Important questions that have not been addressed:

- How would it work?
- How much would it cost?
- How would it be implemented / integrated?
- How does it compare to other scenarios in terms of cost and sustainability?

Cannot answer all questions today but can get started…

Design & model the system (how would it work)

Desired output

- Electricity storage cost and fuel cost for a given set of inputs

$$C_{total} = C_{capital,stack} + C_{capital,storage} + C_{capital,fuel\text{-}synth} + C_{oper}$$

current density
capacity factor
manufact. cost

i-U op. pt.

efficiency
electricity cost
O&M

functions of time

Must be done iteratively.

Balance of material + energy flows, and cost optimization.

See also for electrolysis-only analysis:
[C. *Graves, S.D. Ebbesen, M. Mogensen, K.S. Lackner, Renewable and Sustainable Energy Reviews 15 (2011) 1-23*]

First, decisions

- Redox chemistry ($H_2 + O_2 \leftrightarrow H_2O$, $C + O_2 \leftrightarrow CO_2$, etc)
- Operating points (current-voltage)
- % reactant conversion (like fuel utilization but for electrolysis as well)
- Power supply profile, power demand profile, heat & fuel demand
- Operating strategy

Design & model the system (how would it work)

Redox chemistry

Impacts:

- Storage cost
- Efficiency
- Cell cost

Ideal to cheaply store, but pay more for conversion

gas liquid solid

Store heat

Reaction	theoretical (thermo.) round-trip efficiency at 800 °C
$H_2 + O_2 \leftrightarrow H_2O$ (or H_2O)	75% (87%)
$CO + O_2 \leftrightarrow CO_2$	76%
$C + O_2 \leftrightarrow CO_2$	100%
$CH_4 + 2O_2 \leftrightarrow CO_2 + 2H_2O$ (or $2H_2O$)	100%
$2NH_3 + 1.5O_2 \leftrightarrow N_2 + 3H_2O$ (or $3H_2O$)	100%
$H_2 + Br_2 \leftrightarrow 2HBr$	100%

Deviations from theoretical efficiencies:

- Storage of reactants and products is not unlimited in size nor free, nor is pumping them (need significant reactant conversion)
- Cell manufacturing is not free – a certain electrochemical reaction rate must be attained
- Imperfect heat transfer

In the conventional case ($H_2/O_2/H_2O$), $\Delta H > \Delta G$. For some other redox chemistries, it is the opposite.

Design & model the system (how would it work)

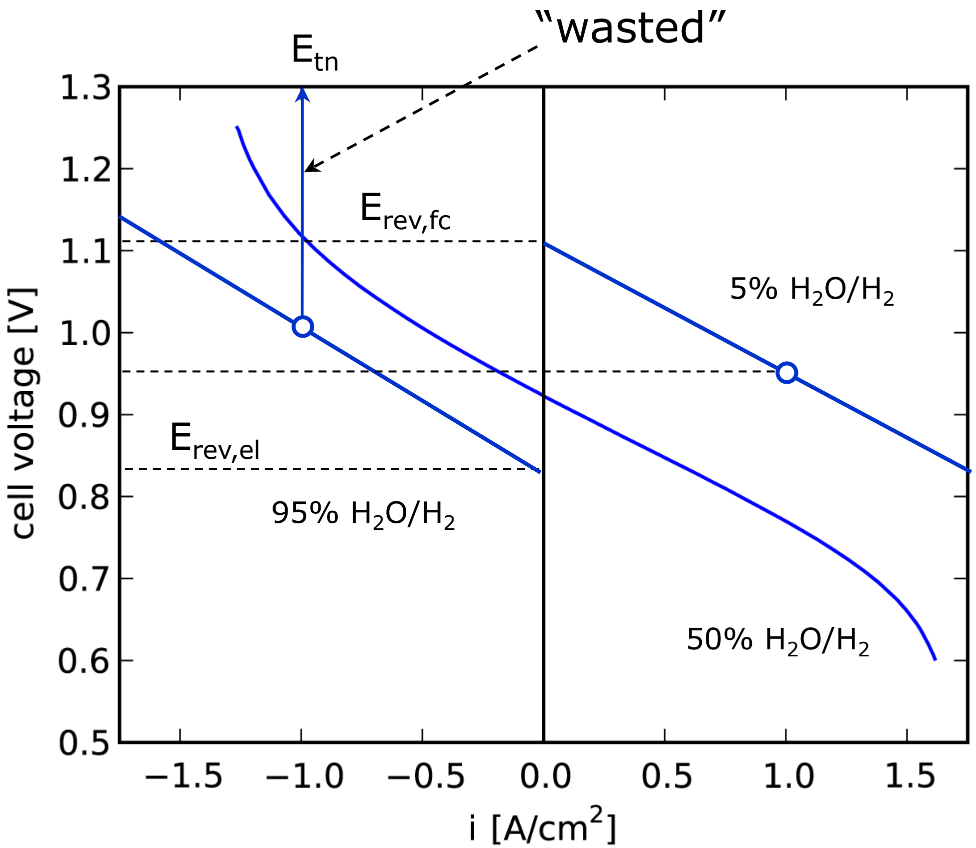
Operating points (current-voltage)

- Example redox chemistry: $H_2 + O_2 \leftrightarrow H_2O(g)$

Example: 1 A/cm²
in both directions

Round-trip efficiency =
0.96 V / 1.29 V = 74%
+ heat transfer losses

BUT is same current / power in both directions a realistic balancing operating point??



Design & model the system (how would it work)

Operating points (current-voltage)

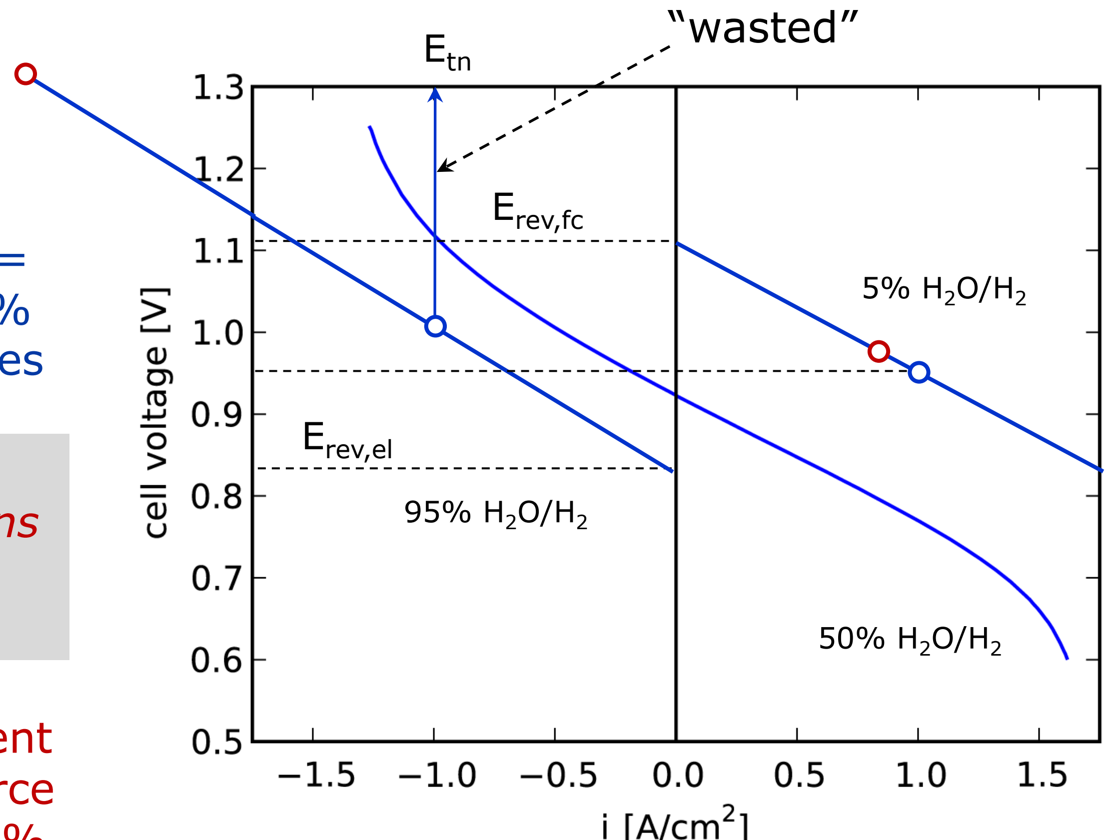
- Example redox chemistry: $H_2 + O_2 \leftrightarrow H_2O(g)$

Example: 1 A/cm² in both directions

Round-trip efficiency = 0.96 V / 1.29 V = 74% + heat transfer losses

BUT is same current / power in both directions a realistic balancing operating point??

Only if your intermittent renewable power source supplies at exactly 50% capacity factor.



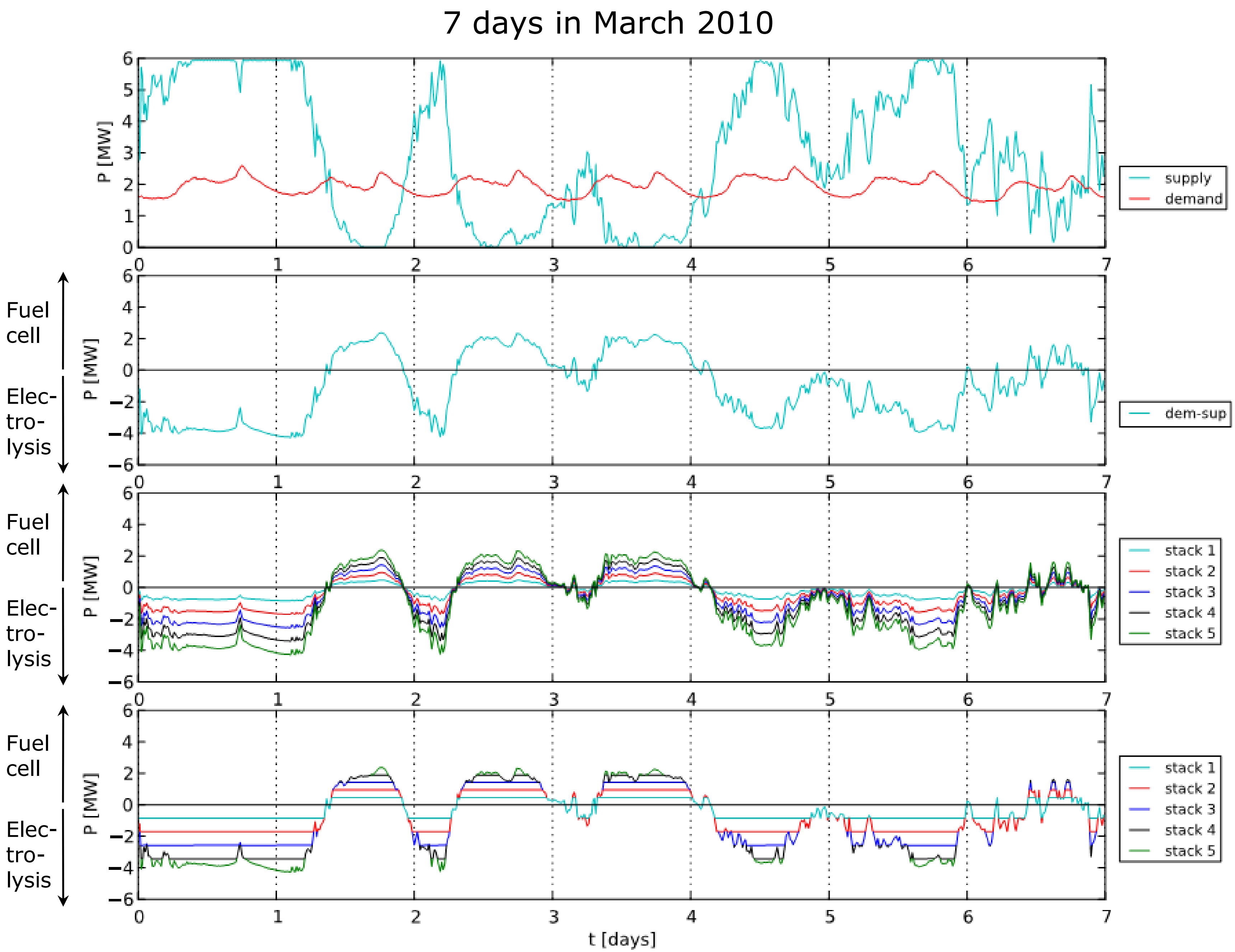
Solar supplies at ~20-25% capacity, so $P_{el} = 4\ P_{fc}$

In this case, different redox chemistries do not affect efficiency even if ΔH and ΔG are closer to equal.

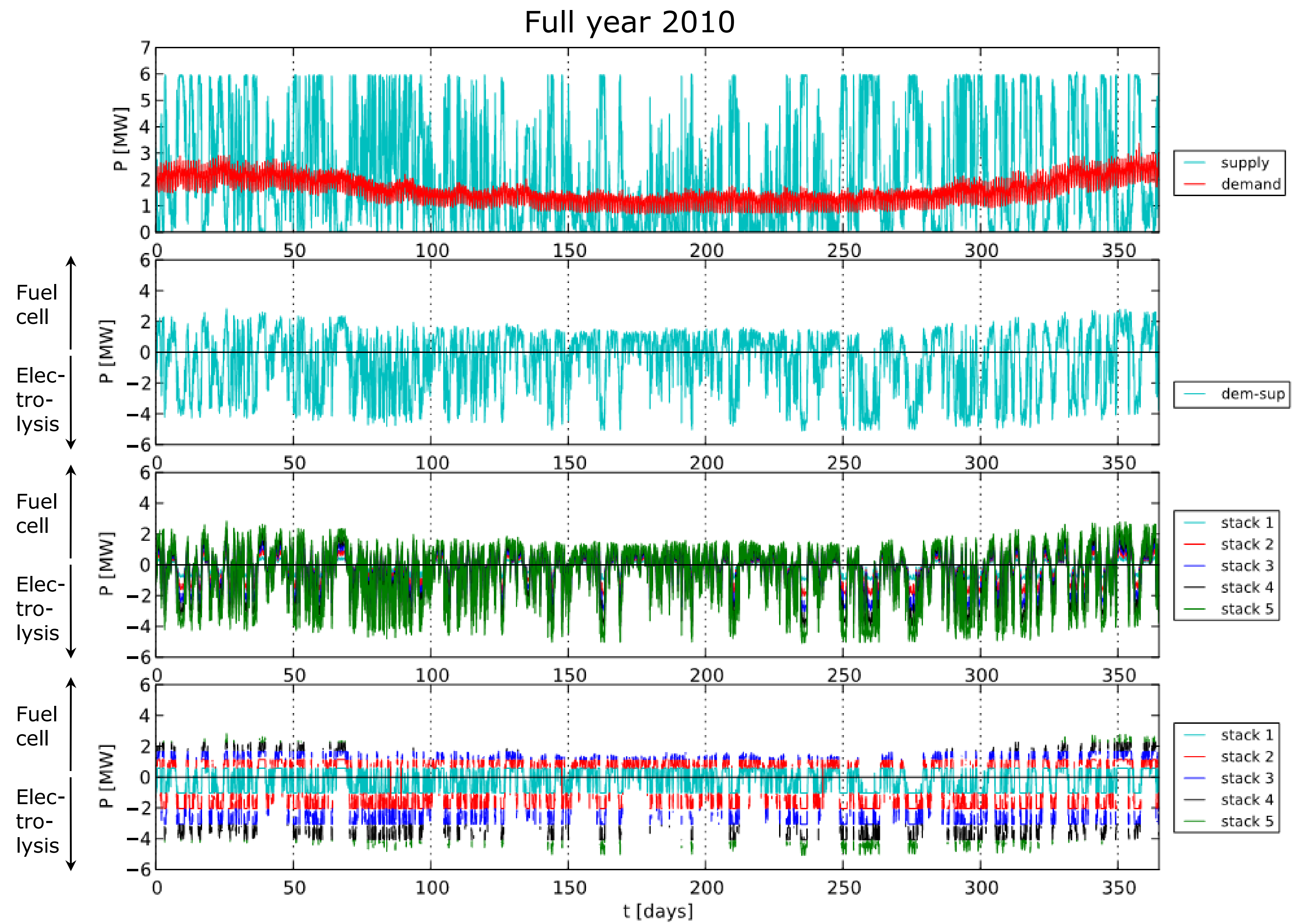
Design & model the system (how would it work)

Power supply profile, power demand profile, heat & fuel demand

- Affects the operating ratio just discussed
- Case study – Ærø island in Denmark, already supplies 50% of its power by wind and wishes to be a 100% renewable island, and data was available ☺



7 days in March 2010
P [MW]
supply
demand
Fuel cell
Elec-tro-lysis
dem-sup
stack 1
stack 2
stack 3
stack 4
stack 5
t [days]



Full year 2010
P [MW]
supply
demand
Fuel cell
Elec-tro-lysis
dem-sup
stack 1
stack 2
stack 3
stack 4
stack 5
t [days]

Model output (How much would it cost?)

- Wind power capacity factor = 0.36
- Average ratio of charge to discharge power = 1.9 (for round-trip electricity-to-electricity efficiency of 61%)
- Using similar assumptions as our CO_2-to-fuel estimates mentioned earlier (0.25 Ω cm^2 stack ASR, 10 yr life, $400/kW SOFC DOE SECA goal met), and assuming low cost 4 cents per kWh for intermittent wind power preliminary cost estimate:

$$C_{elec\ storage} = C_{capital,stack} + C_{capital,storage} + C_{oper} - P_{heat\ delivered}$$

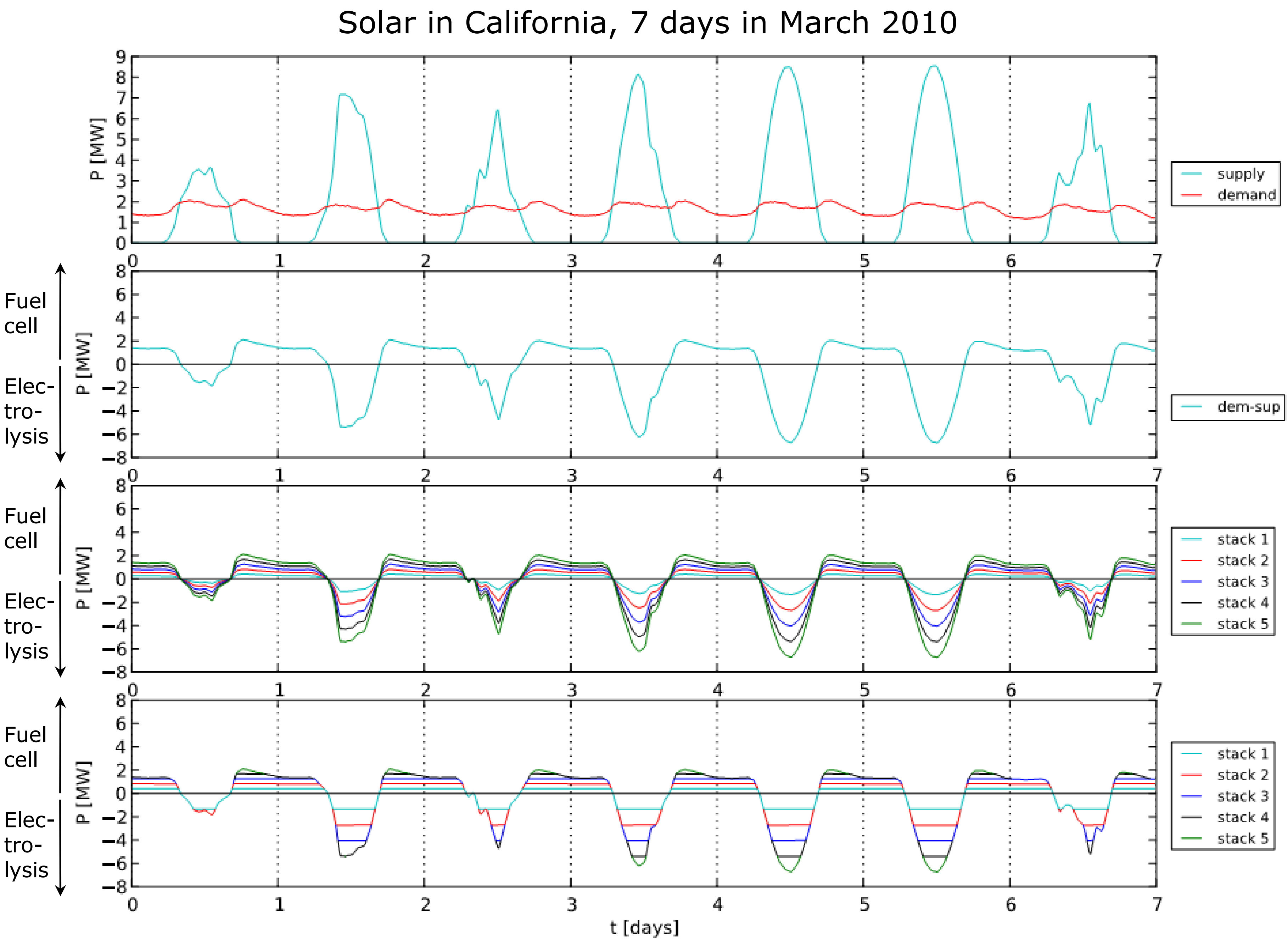
$0.016/kWh

1.6 x electricity price + O&M

Even for hydrogen, estimated in literature <$0.006/kWh

So at 4 cents per kWh intermittent wind power,
we're talking about 8-9 cents per kWh for on-demand power.

- And it appears that fuels can be co-produced with a high net capacity factor for the stack, due to multi-use.



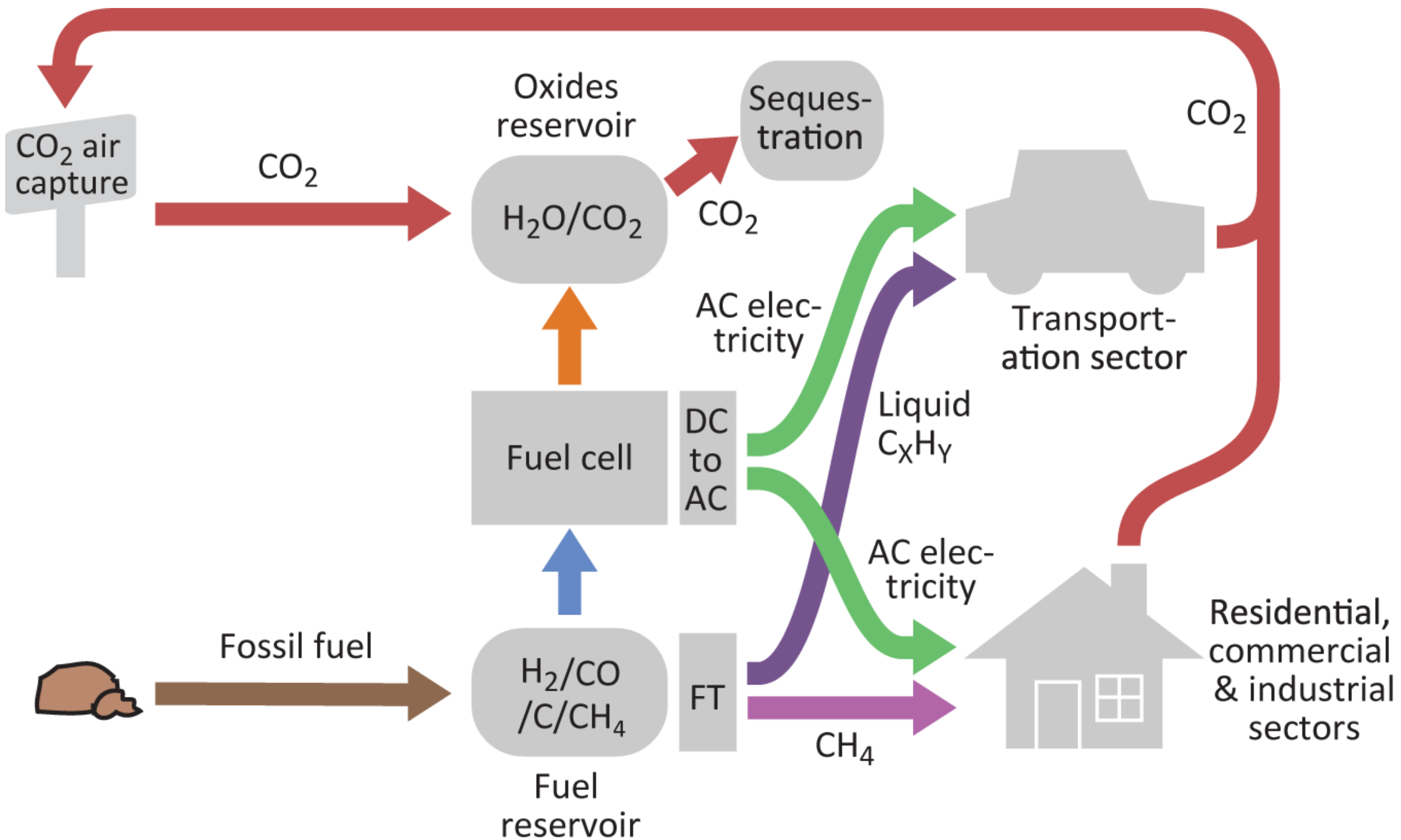
Solar in California, 7 days in March 2010
P [MW]
supply
demand
Fuel cell
Elec-tro-lysis
dem-sup
stack 1
stack 2
stack 3
stack 4
stack 5
t [days]

How would it be implemented / integrated?

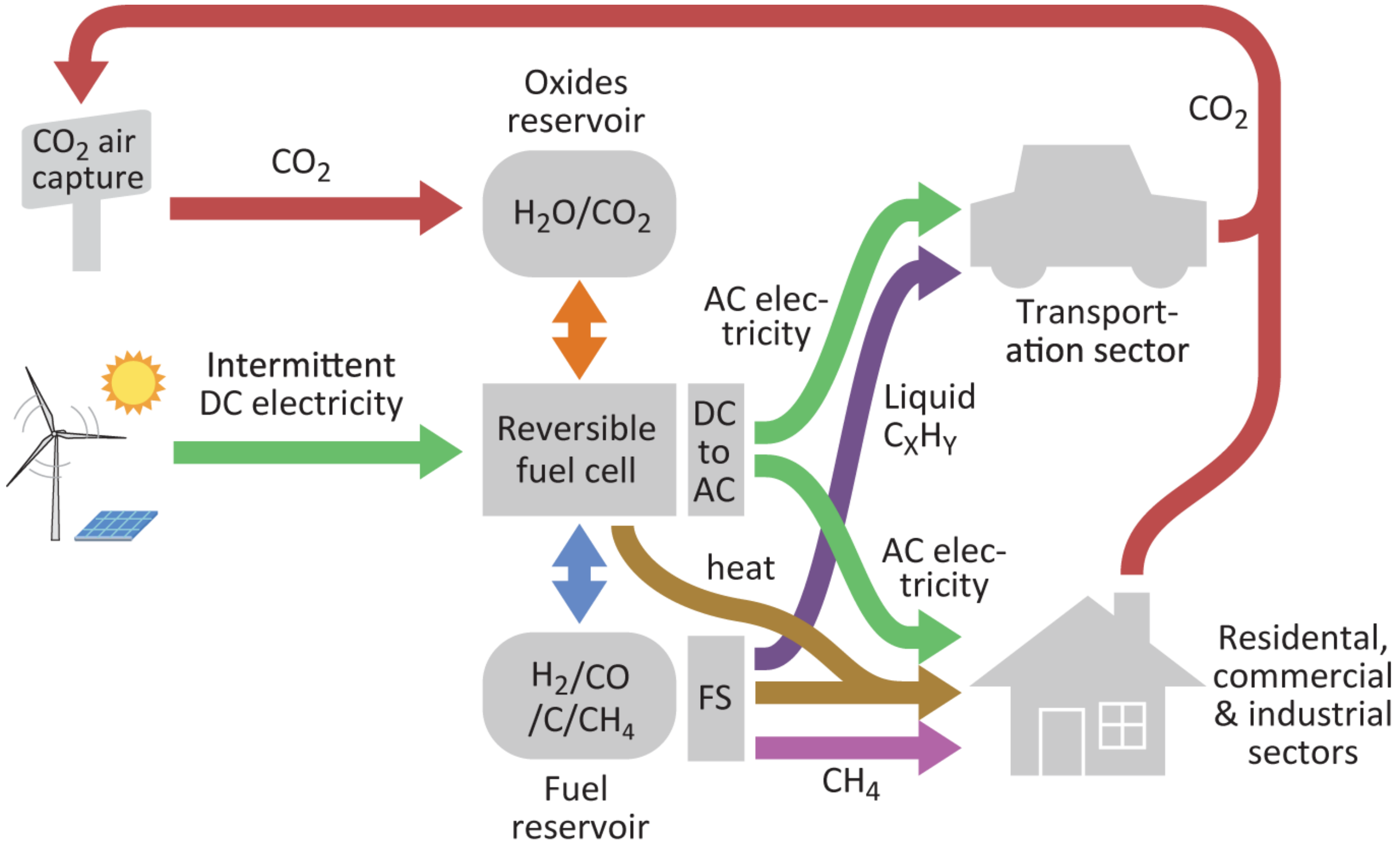
- In most regions of the world today where fossil fuel dominates, reversible fuel cells can be installed as conventional power plants at first and operated exclusively in fuel cell mode.
- As the fraction of solar and wind power grows, these power plants can be operated reversibly to provide energy storage.
- Therefore, no need to install storage capacity at first (may need to install some additional power electronics though)
- They are only energy storage technology that can also compete in the power generation market (converting fossil fuels to electricity) as well as the transportation fuel market (producing hydrocarbons using non-fossil electricity, e.g. solar fuels).
- In fact because such cells can operate on CH_4, they will be "competing with themselves" – this versatility will allow one to choose which energy supply is lowest cost and which demand gives the highest price.

Versatility:
- Affordability
- Transition to renewables

Reversible fuel cells – transition from fossil fuels to renewables



Reversible fuel cells – transition from fossil fuels to renewables



Conclusions

- A system based on reversible fuel cells applied for wind/solar electricity storage, with co-production of liquid hydrocarbon fuels, was designed and a simple model was (+ is being) made
- The energy supply and demand data can be used to obtain optimal operating parameters (e.g. i-U operating ratios for fuel cell vs electrolysis modes of operation)
- Preliminary economic analysis using the model shows that such a system is a promising long-term solution for 100% renewable electricity + fuels
- If SOFC power plants become economical (e.g. cost goals are met), it seems likely that reversible operation for electricity storage and for synthetic fuel production becomes economical – and do not need to be deployed especially as storage devices, an additional economic advantage.
- The estimated storage cost is quite a bit cheaper than batteries, which are significantly more efficient. Efficiency and capital cost are tied together: increasing efficiency is only important to the extent that it does not increase the total cost.

Thank you!